Influence of channel shape on wave generated parameters by a pressure source in shallow water

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Abstract

The present work is a numerical investigation into the waves generated by a pressure source moving in straight channels with a non-rectangular cross channel depth profile. Wave fields generated by the moving pressure source are described, and the effects of channel bathymetry on the generated wave

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characteristics; wave height, wave breaking location, wave breaking type and intensity, and peel angle are presented. Four different channel cross-section shapes were investigated and the results were analysed.

It was concluded that maximum wave height depends on pressure source parameters and the channel shape does not have significant effect on the maximum wave height. All four investigated channels were able to generate plunging shaped breaking waves. In additon, it was found that wave breakig intensity and barrel shape can be controlled by beach slope shape, however, beach slope does not have considerable effect on the wave breaking location. The width of deep-section of channel has significant effect on the breaking location. Widening the deep-section of the channel moves the breaking point further from the pressure source. According to the simulation results, it is possible to generate waves for intermediate to expert levels only by changing the pressure source speed. According to the results, by changing the pressure source speed, the peel angle changes and is the best way to change the required skill level for surfing and also, changing the channel shape does not have significant effect on required skill level for surfing.

Keywords: Shallow water wave, Wave breaking type, Wave breaking intensity, Peel angle

Introduction

Vessel generated waves

Usually the wave generated by high-speed vessels moving in shallow water is considered in terms of environmental and safety hazard in confined waters. Creating vessel generated waves, disturbing other vessels in ports and harbours, shoreline erosion and its impact on marine life are some of the most important issues in this field (Macfarlane 2012). Field studies have been conducted on several locations where problems of this nature have occurred (Nanson, Krusenstierna et al. 1994, Macfarlane and Cox 2004, Macfarlane, Cox et al. 2008).

The wash waves generated by vessels can be characterized in terms of the hull shape (Renilson and Lenz 1989) and operating condition (Robbins, Thomas et al. 2011). Due to the great interest in wake-wash effects, a considerable amount of research effort has been conducted in the last years. In model experimental studies the focus has been on designing low-wash ships and acquiring reliable data for validation (Zibell and Grollius 1999, Koushan, Werenskiold et al. 2001, Macfarlane and Bose 2012).

Effect of waterway bathymetry

Waterway bathymetry has influence on the wash wave generated characteristics. Natural and man-made water channels often have non-rectangular cross sections. It is important to understand how channel geometry affects the evolution of waves in water channels of arbitrary shape. Several researchers have studied waves propagating in channels with arbitrary cross-section profiles (Peregrine 1966, Peters 1966) and the wave patterns, in two horizontal dimensions generated by a disturbance moving at speeds close to the critical Froude number in channels with a rectangular cross-section profile(Ertekin, Webster et al. 1986, Katsis and Akylas 1987, Pedersen 1988). Mathew and Akylas (Mathew and Akylas 1990) studied waves propagating in channels with a trapezoidal cross-section profile. Teng and Wu (Teng and Y.Wu 1997), Jiang et al.(Jiang, Henn et al. 2002). and Liu and Wu (Liu and Wu 2004) have made contributions to this field of research. According to their results, the wavelength and time period of wave generation were affected by both the submerged channel cross-sectional geometry and the channel sidewall slope at the waterline. Most of these studies deal with channels with trapezoidal cross-section profiles, but Jiang et al.(Jiang, Henn et al. 2002) include results for a channel with a deep trench along the centre line. They used a method based on Boussinesq-type equations for the far-field flow and on slender-body theory for the near-ship flow and they showed this method is able to predict 2D wave propagation and waves far from the vessel in a rectangular channel.

Waves for surfing

In addition to these reasons for conducting wake wave studies, such waves can be considered with respect to the wave surfing. A new surf pool concept was developed by Greg Webber and his idea to produce continuous breaking waves was patented (Webber 2004, Webber 2006) by Liquid Time Pty Ltd. This invention is based on a circular pool in which the surfing waves are created continuously along the banks of the pool (Schmied, Binns et al. 2011). The idea was born from Webber's experiences surfing in the Clarence River on waves generated behind a fishing boat. Webber's idea is based on one or more pressure sources being rotated within an annular wave pool to generate waves. A pressure source is any object that disrupts the water's surface and creates a wave. The circular channel has sloping bathymetry with the outer side being deeper; the waves are generated in the deep water and break in the shallow water on the inner island (Fig. 1).

Prediction of vessel generated waves

Tools for predicting the near-field vessel generated waves and their propagation to far field with accuracy are needed. Most research has been conducted using theoretical (Chandraprabha and Molland 2004) or experimental (Fontaine and Tulin 1998, Henn, Sharma et al. 2001) approaches. In numerical simulations, the focus has been on developing efficient methods. For a ship moving in water of uniform depth, linear and nonlinear theories can be applied usefully in the subcritical and the supercritical speed range (Raven 2000, Yang, Faltinsen et al. 2001). Thin ship theory can be used for the wave generated by a ship moving in a channel. This theory provides an alternative to higher order panel methods for estimating wave resistance when applied solely to slender hulls (Chandraprabha and Molland 2004), but it is not valid for unsteady cases and transom stern flow separation (Yang, Faltinsen et al. 2001). More general shallow water approximations are obtained from Boussinesq type equations, which are valid for most arbitrarily unsteady cases. Boussinesq's equations based on a suitable reference level were used for computing ship waves in shallow water. However this method is not able to predict the 3D flow pattern around the vessel (Kofoed-Hansen, Jensen et al. 2000). An alternative is to combine the thin ship theory and the Boussinesq method. This hybrid approach combines a steady nonlinear panel method for the near-ship flow with a Boussinesq solver for the far-field wave propagation (Yang, Faltinsen et al. 2001). However, this method is only useful for steady problems. It should be noted that due to the nonlinear and unsteady nature, as well as the large domain feature of the wash problems, they cannot solved well by the linear wave theory nor approximated efficiently by nonlinear singularity methods. Typically, the finite volume method has been used to predict the wave generated and its propagation (Kofoed-Hansen, Jensen et al. 2000, Kim 2003).

Wave parameters for surfing

The wave breaking location, breaking type and intensity, and peel angle are most important characteristics which should be considered for generated waves for surfing purposes. It is well known that a wave will break in different shapes depending on the beach slope, wave height and the wavelength perpendicular to the beach slope. The types of breaker shapes were defined by Galvin (Galvin 1968). There are some existing methods that can be used to describe wave breaking characteristics such as Iribarren number (Black and Mead 2001). The Iribarren number is defined as:

$$\xi = \frac{\tan(s)}{\sqrt{H_{breaking}/\lambda_s}} \tag{1}$$

where s is the beach slope, $H_{breaking}$ is wave height at the breaking point and λ_s is the offshore wavelength perpendicular to the direction of wave propagation. The wave breaker type can be predicted based on value for ξ:

$$\begin{cases} \xi < 0.4 & \text{Spilling} \\ 0.4 \le \xi \le 2.0 & \text{Plunging} \\ \xi > 2.0 & \text{Surging / collapsing} \end{cases}$$

However, while these methods give an indication of breaker type, studies of surfing wave shape have found that they do not accurately differentiate the transition between breaker categories (Mead 2003).

The cubic curve method is a method for predicting the shape of a plunging wave and wave breaking intensity (Sayce, Black et al. 1999). In this method a cubic curve is fitted to the crest parallel images of breaking waves and vortex length (l), vortex width (w), vortex breaking angle (θ) and wave height are calculated (Fig. 2). The 'vortex ratio' (tube length to width: Fig. 2) is a measure of the 'roundness' of the tube. As the ratio of vortex length to width approaches 1, the tube shape becomes more circular and the breaking is more intense (Black and Mead 2001).

Peel angle is a term used to describe the speed that a surfer needs to travel successfully across the face of a wave (Mead 2003). The peel angle is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shoreward (Fig. 3). Peel angles range between 0° and 90°, with small peel angles resulting in fast surfing waves and large angles in slow surfing waves. It is possible to classify the surfing skill for all channels by considering the wave height and the peel angle (Mead 2003) (Hutt, Black et al. 2001).

Methodology

In this study, a Computational Fluid Dynamics approach was utilized to predict the motion of the fluid, and hence the free-surface. The CFD software ANSYS-Fluent was used as the flow solver. Previous work by the authors demonstrated that ANSYS-Fluent software is capable of predicting the wave parameters (Javanmardi, Binns et al. 2013, Javanmardi 2015). In this investigation, the effect of channel bathymetry on the key parameters (wave breaking location, breaking type and intensity, and peel angle) was investigated and the results are presented here.

Numerical method

Simulation setups

In this study, a Computational Fluid Dynamics approach was utilized. The CFD software ANSYS-Fluent version 14.0 was used as the flow solver (2011). The governing equations are three-dimensional Reynolds Averaged Navier-Stokes equations for incompressible flows, along with the $k - \varepsilon$ turbulence model. These were solved using the FVM approach. Since the flow is incompressible, a pressure based solver was used.

The volume of fluid approach was used with a time dependent and first order explicit time discretisation scheme. The SIMPLE algorithm was used for pressure-velocity coupling. The PRESTO scheme was used to interpolate the pressure on the cell faces, as this is recommended for VOF simulations (Andersson, Andersson et al. 2012). The Least Squares Cell Based scheme was used for gradient discretisation and momentum was discretized with second order upwind approach. The standard wall function was utilised for $k - \varepsilon$ turbulence modelling.

In this work, to discretize the convective term in the equation for transport of the volume fraction, the High Resolution Interface Capturing scheme (HRIC) was used (Muzaferija, peric et al. 1998).

A variable time step method with Global Courant Number of 5 and 20000 time steps was chosen, with five iterations per time step. The First Order Implicit method was used for transient formulation.

In general, the number of cells in the domain was about 17 millions. Simulation models were executed on 48 nodes at AMC Linux cluster that consisted of quad core, 64 bit system. Typically, each simulation took three weeks to complete.

To predict the wave ehight accurately, the cell aspect ratio is a significantly important parameter. An average aspect ratio of no greater than about 7 is required to predict wave height. Additionally, 10 cells per wave height are sufficient to predict wave height (Javanmardi, Binns et al. 2013). These outcomes were utilised to generate cells in the domains.

Mostly hexahedral meshes were used to discretize the domains. The velocity inlet and outflow conditions were used to specify the inlet and outlet boundary conditions and the remaining boundary surfaces along the exterior of the domain were set to no-slip wall conditions.

The simulations were accomplished using moving reference frames (MRF) with Fluent ANSYS providing these for both translating and rotating systems.

Validation

The experimental results, obtained from tests conducted at the AMC towing tank, were compared with the numerical predictions in earlier work (Javanmardi, Binns et al. 2012, Javanmardi, Binns et al. 2013). The wavedozer wich used as a pressure source was a wedge shape body with constant beam (Driscoll and Renilson 1980). Towing tank tests were conducted in a water depth of 1.5 m with a wavedozer of 0.3 m beam and 0.1 m draft. Fig. 4 to Fig. 6 present the wave time history for $Fr_h = 0.7$ at three different lateral distances. Since the first wave behind the pressure source was important for this study, the simulations' convergence checked by monitoring the continuity residuals and characteristic of the first generated wave behind the pressure source and the simulations were ceased as soon as the first generated wave height reached to a steady level. Fig. 7 shows the comparison of maximum wave height of numerical and experimental results at varying lateral distances for different depth Froude numbers, where depth Froude number is based on the (Javanmardi, Binns et al. 2012)depth under the wavedozer and is defined by equation (7):

$$Fr_h = \frac{V}{\sqrt{gh}} \tag{7}$$

where V is wavedozer speed (m/s), g is gravitational acceleration (m/s^2) and h (m) is depth of calm water in the deep-section of the channel.

As can be seen from Fig. 4 to Fig. 6, and from (Javanmardi, Binns et al. 2012, Javanmardi, Binns et al. 2013) the numerical simulations were able to adequately predict the experimental results, thus giving confidence in the use of this approach to investigate the effect of bathymetry on the generated waves.

Test geometries

The validated numerical approach discussed above was used to investigate the influence of channel shape on the wave pattern generated by a pressure source. For all the cases a wavedozer was used as the pressure source. The concept of the wavedozer is explained in (Driscoll and Renilson 1980). A schematic of the wavedozer used for this study is given in Fig. 8.

Four channels with the cross-sections as shown in **Error! Reference source not found.** were used. In each case the wavedozer was located adjacent to the wall on the left hand side.

For the simulation, 144.5m of channel length with a downstream domain of 84m was modelled. The depth of water at the deep-section of channel was 3.75 m in each of the cases. Approximately 17 million cells were used, based on mesh density studies conducted earlier (Javanmardi, Binns et al. 2013).

The depth Froude number was altered by changing the velocity. The focus of the work was on depth Froude numbers close to one, as this had already been shown to be the value which gives the best quality for surfing (Javanmardi 2015).

Results and discussion

Wave height and breaking location

Error! Reference source not found. presents free surface elevation for Channel 1 at depth Froude number of 0.95. Fig. 11 presents the predicted wave height at different lateral distances for various depth Froude numbers. It can be seen that it is possible to generate larger wave by increasing wavedozer's speed. To find the breaking point location, the numerical results were post-processed by generating a plane at different lateral distances and observe the shape of free-surface. The open markers in the figures show the start of wave breaking at different depth Froude numbers. It can be seen that for all Fr_h, the wave starts to break around 14 m lateral distance except for $Fr_h = 0.8$. At $Fr_h = 0.8$, the breaking point is close to the pressure source. In addition, the wave at $Fr_h = 0.9$ has two breaking points. Depth-limited breaking occurs when orbital velocities, increasing towards the beach exceed the wave phase speed which decreases in the landward direction. Generally, the depth-limited breaking happens where $0.35 < \frac{H_b}{h_b} < 0.5$, where H_b is related to the breaking wave height and h_b *is* water depth at breaking . According to Nelson (Nelson 1997) the depth-to-wave height ratio cannot exceed 0.55. To investigate whether the breaks are depth-limited breaking, wave heights and water depth at breaking points were summarized in Table 1. According to Table 1, the depth-to-wave height ratio (*H/*h) for all breaks is less than 0.55. Only the first breaks at $Fr_h = 0.8$ and $Fr_h = 0.9$ (close to wavedozer) are out of the depth-limited breaking condition, while other breaking points are in the interval.

Since nearly all of the waves break at around 14 m lateral distance, it was thought to be possible to move the breaking point further from the pressure source by changing the bathymetry for y greater than 13.5m (0.5m before the breaking point) and making the cross-section plateau as shown in **Error! Reference source not found.**. This configuration was simulated at two Fr_h values of 0.8 and 0.99. The results for the two different channel configurations are compared in Fig. 12 for $Fr_h = 0.8$, and 0.99. The break point for Channel 2 configuration occurred at the same position as in Channel 1 for both the simulated values of Fr_h. It was concluded that changing the bathymetry beyond y=13.5 m does not have any significant effect on the location of break point.

Since changing the bathymetry for y greater than 13.5 did not change the location of breaking point, it was assumed that the wave is completely developed before y=13.5m such that changing the bathymetry only half a meter before the break point (14m) does not have any influence. Thus, the effect of the lateral position of the toe of the beach was investigated using a third channel geometry, channel 3 (see **Error!**

Reference source not found.). For this geometry the flat bathymetry starts at y = 12 m from the wall. This configuration was simulated at $Fr_h = 0.99$. According to the results (Fig. 13), it is clear that changing the bathymetry did not have any effect on the breaking point nor on the wave height before breaking.

In the next configuration (Channel 4), the slope of the bathymetry was kept identical to Channel 1, but the width of the deep-section of the channel was increased to 12m (Fig. 9). The wave heights were almost the same for all four channels at the same pressure source speed ($Fr_h = 0.99$). Comparing the results of Channel 4 with previous results showed that increasing the width of the deep-section of the channel causes the wave breaking point to move further from the pressure source (closer to the beach), Fig. 13. Widening the channel by three meters causes the breaking point to move 4 m. Since generated wave does not breaking the deep-section of channel 1 at Fr_h=0.99, widening the deep-section moves breaking point further from the wavedozer. Additionally, there is decrease in the wave height in the deep-section in Channel 4 compared to Channel 1(see Fig. 13) which causes the height-to-water depth ratio on the beach for Channel 4 becomes less than Channel 1. Therefore, to compensate the decrease, the breaking point moves more than 3 meters added to deep-section.

Wave breaking type and intensity

Several factors affect the category that waves fall into when breaking (spilling, plunging, collapsing or surging), such as wave height and wave length, wind strength and direction. However, the bathymetry has most influence on the shape of breaking waves. The transition of breaker shape, from spilling through to surging, is mainly a result of increasing the seabed gradient. On low gradient seabeds, waves break with a spilling form. As seabed gradients increase, breaker form tends towards plunging, and finally to collapsing or surging waves on very steep gradients.

As explained previously, Iribarren number can be used to describe wave breaking characteristics. **Error! Reference source not found.** shows that the generated wave plunges for channel 3 at Fr_h=0.99. Due to the following reasons, the Iribarren number cannot be used to predict wave breaking type in this case. Simulation results for Channel 2 and Channel 3 indicate that it is possible to have the plunging breaking type (see **Error! Reference source not found.**) where the beach slope is zero, while according to the Iribarren, waves spill over low gradient bathymetry. In addition, the Iribarren number was defined for waves with crests perpendicular to the beach, while the waves generated by moving pressure sources have an angle relative to the beach. Therefore, it is proposed that it is inappropriate to use the Iribarren number to quantify the wave breaking intensity in this study.

The cubic curve method is a method for predicting the shape of a plunging wave and wave breaking intensity. Fig. 15 compares the experimental and numerical wave breaking shape and proves that numerical approach is able to predict shape of plunging waves. To identify the vortex ratio for different channel shapes, the numerical results were post-processed by generating a plane at the distance where the wave plunged. The vortex ratio is manually measured at the moment wave lip just touches the water. The maximum length of vortex was chosen as vortex length and the maximum width perpendicular to the vortex length was selected as vortex width. Table 2 shows the measured vortex ratio for different channels. It is clear that the breaking shapes for the different channels are different. As a general conclusion, the channel slope shape has an effect on the breaking intensity. In addition, Channel 1 has the highest vortex ratio and Channel 4 has the lowest. The water depths at breaking point for Channel 1 and 4 are 1.25 and 1.08 m and the wave heights are 0.9 and 0.91 m respectively. Therefore, the wave height-to-water depth ratio for Channel 4 is bigger than Channel 1 that has effect on wave breaking intensity. From this conclusion it can be further concluded that Channel 1 has lowest intensity and Channel 4 has highest.

Peel Angle

By finding the position of wave peak at different lateral distances, the average peel angle was calculated. Table 3 and Table 4 show the average peel angles and surfing skills for different Fr_h and different channel shapes. According to the results, the best way to change the required skill level for surfing is to change the pressure source speed and changing the channel shape does not have significant effect on required skill level for surfing.

Concluding remarks

In this study, the influences of channel parameters on wave characteristics were investigated. Four full scale channels with different cross-sections were modelled, with the effect of beach slope and channel shape on the wave breaking location, wave breaking type and intensity, and peel angles investigated. It is possible to generate larger wave by increasing wavedozer's speed. The wave heights were almost the same for all four channels at the same pressure source speed ($Fr_h = 0.99$). It was concluded that channel shape does not have significant effect on the maximum wave height and the maximum wave height is function of pressure source parameters. In terms of wave breaking intensity, all four channels were able to generate plunging shaped breaking waves. Beach slope shape has an effect on wave breaking intensity, while it does not have considerable effect on the wave breaking location. The width of deep-section of channel has significant effect on the breaking location. Widening the deep-section of the channel moves the breaking point further from the pressure source. It was concluded that Iribarren number could not be used to determine the wave breaking type in these cases. The cubic curve method was used to specify the wave breaking intensity. The vortex ratio for each breaking wave was measured. It was found that changing the beach slope had an effect on the barrel shape. The peel angles were extracted from simulation results for different Fr_h and different channels. Based on Hutt's chart, the surfing skill level for different channels and different speeds were considered. According to the simulation results, it is possible to generate waves for intermediate to expert levels by changing the speed. By comparing the results for all channel configurations, two important conclusions can be made. Firstly, in terms of construction costs and commercial considerations, Channel 1 is the most successful, because it is possible to generate a wave with the same height as the other channels while this channel is the narrowest, thus needing the least materials and would have the lowest construction cost. Secondly, in terms of surfing, since the breaking point in Channel 4 occurs further from pressure source than other channels, the surfable wave width is larger than other waves which gives more space to surfers for manoeuvring.

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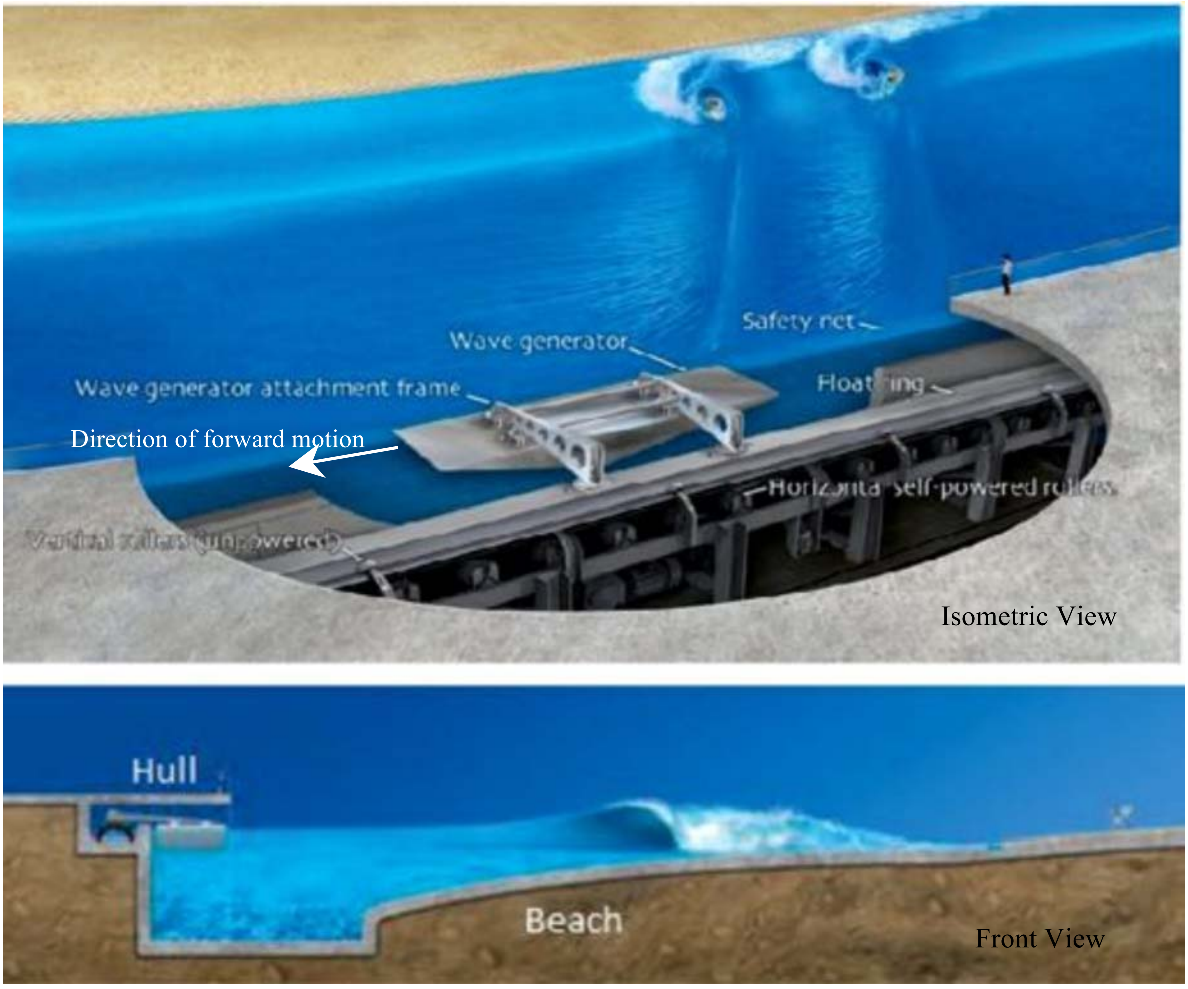


Fig. 1 : Wave pool concept (reproduced with perission of Liquid time Pty Ltd)

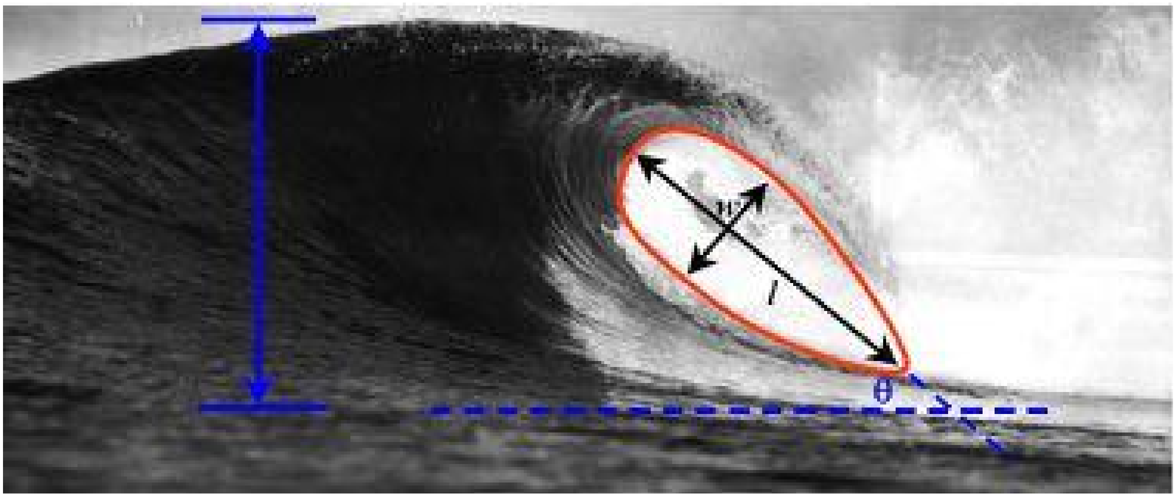


Fig. 2: Curve fitting method (contain data from (Sayce, Black et al. 1999))

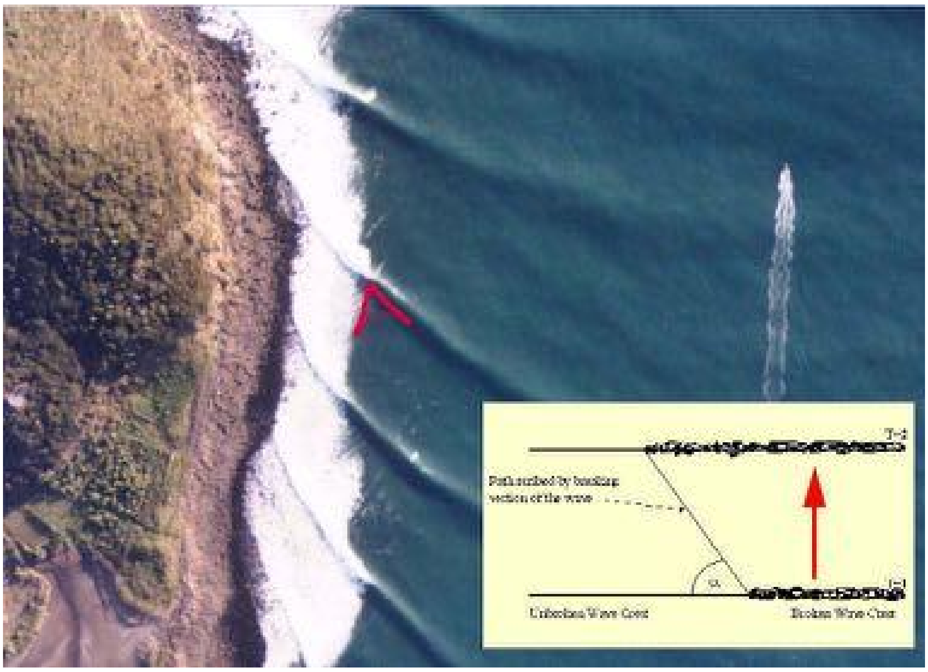


Fig. 3: Schematic diagram of wave peel angle, α. (contain data from (Mead 2003))

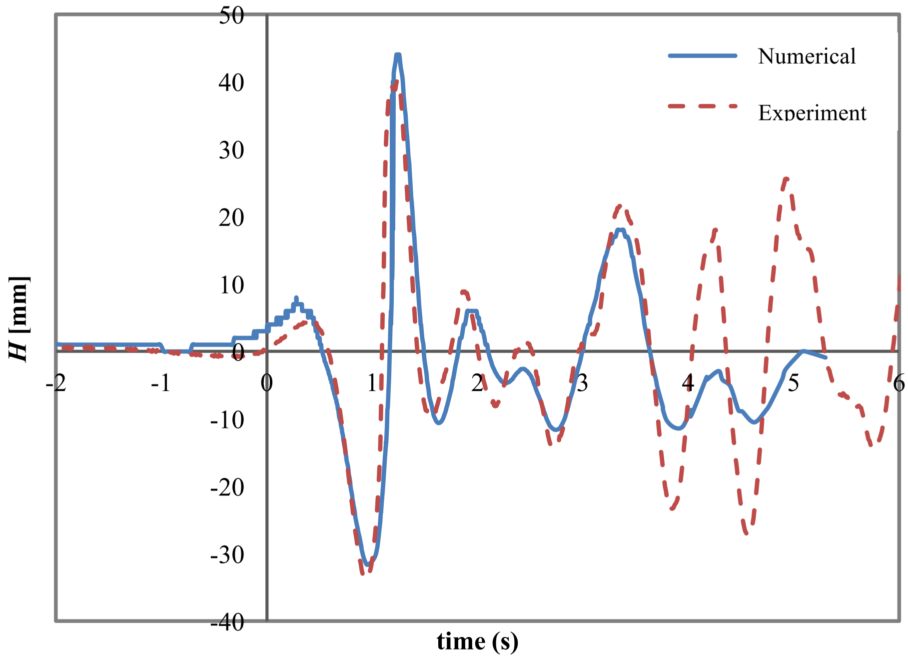


Fig. 4: Wave height time history for Fr_h=0.7 at 0.75m lateral distance from centre-line (WP1)

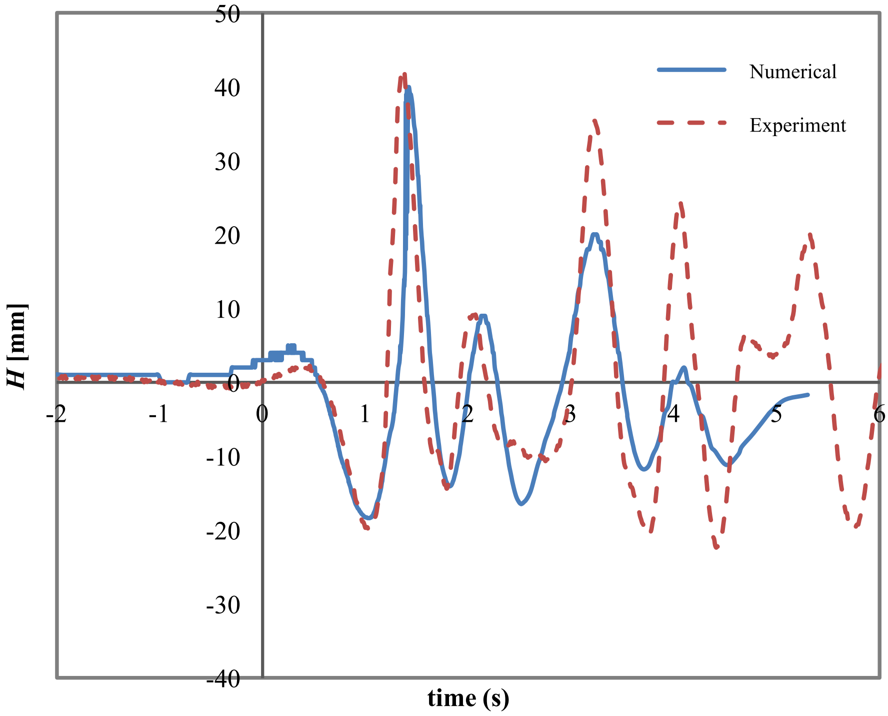


Fig. 5: Wave height time history for Fr_h=0.7 at 1.0m lateral distance from centre-line (WP2)

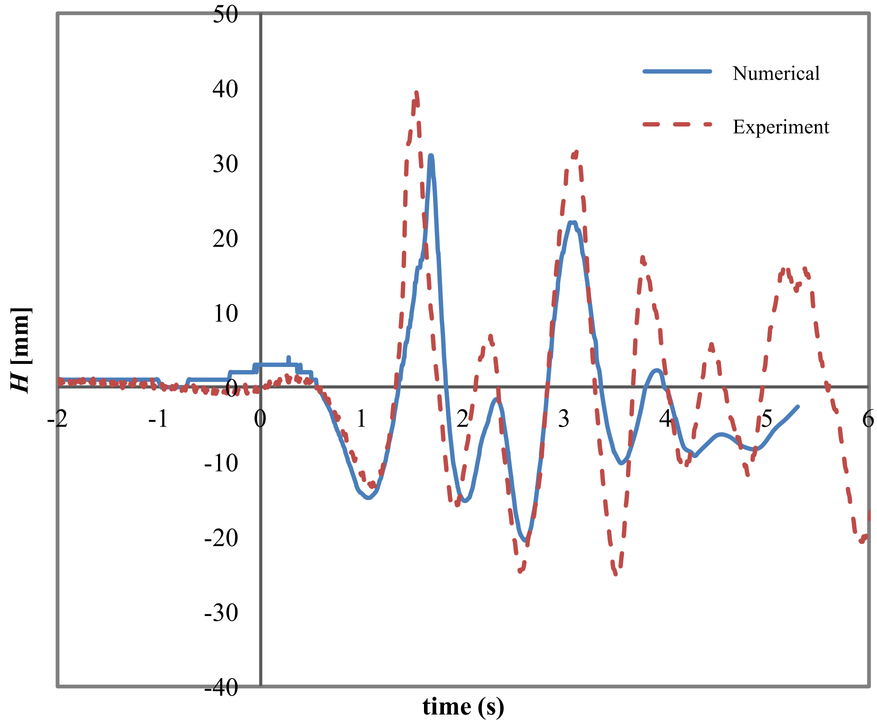


Fig. 6: Wave height time history for Fr_h=0.7 at 1.25m lateral distance (WP3)

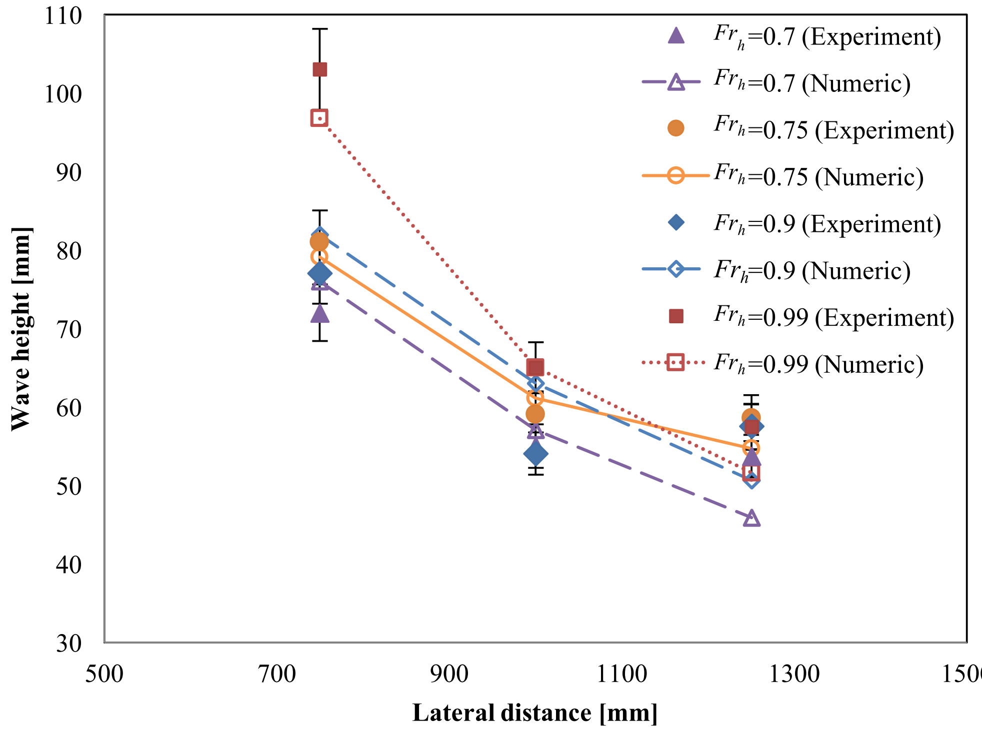


Fig. 7: **Comparison of maximum wave height of numerical and experimental results at varying lateral distances for different depth Froude numbers, the horizontal axes presents the distance from from centre-line**

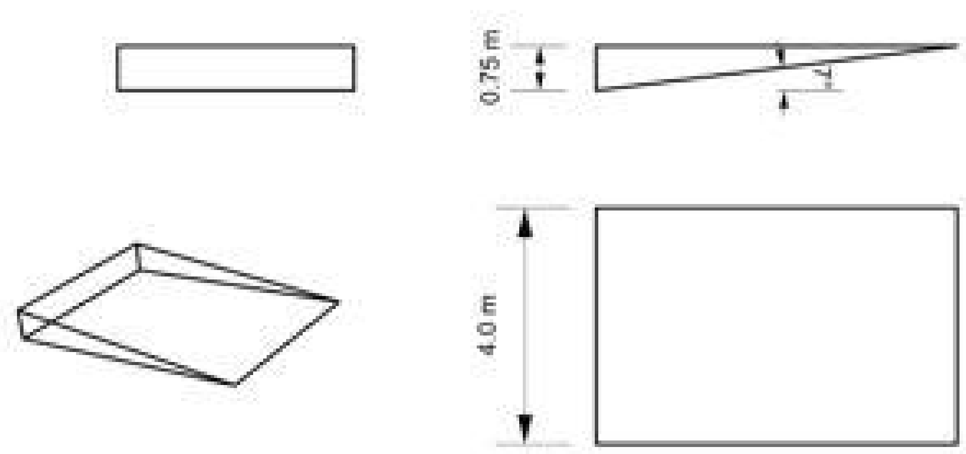
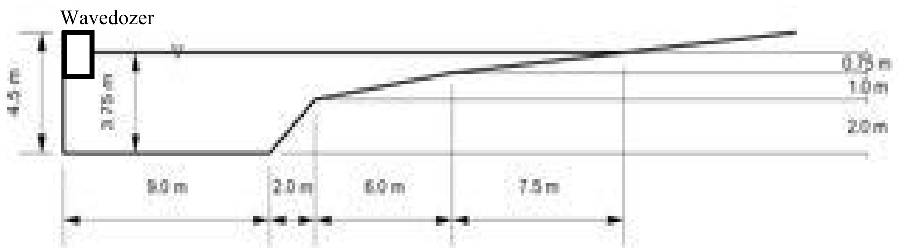
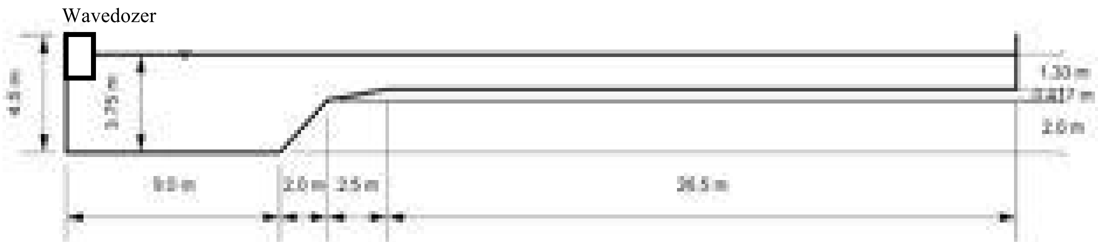


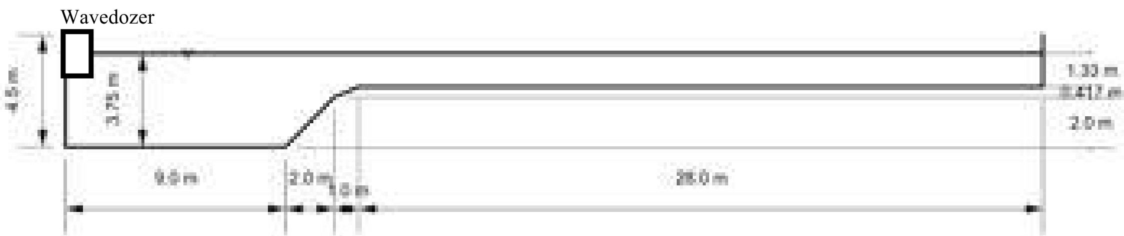
Fig. 8: Wavedozer of beam=4.0 m, draught=0.75 m, angle of attack= 7 degrees



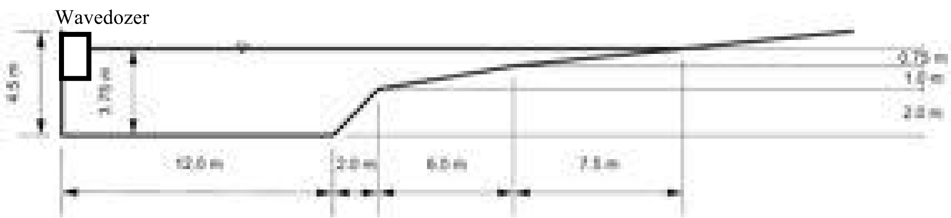
Channel 1



Channel 2



Channel 3



Channel 4

Fig. 9: Investigated channels' parameters

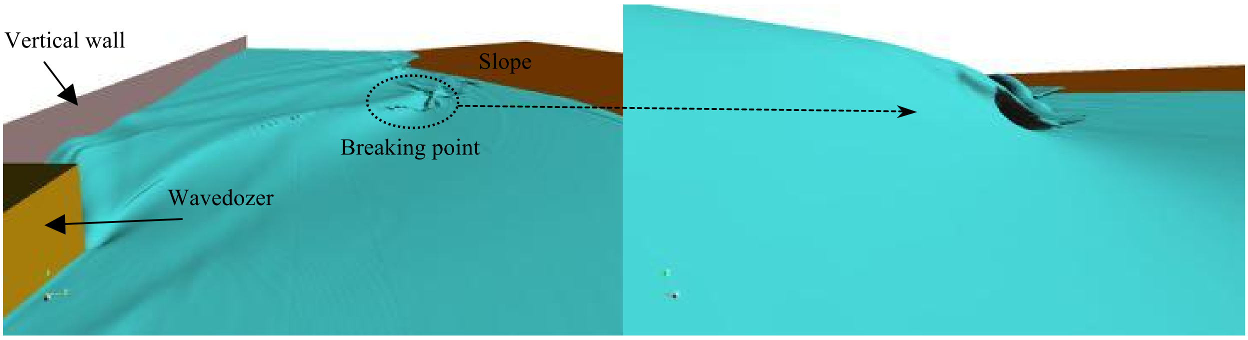


Fig. 10: Free surface elevation for Channel 1 at Fr_h=0.95 at the same time instant but different views

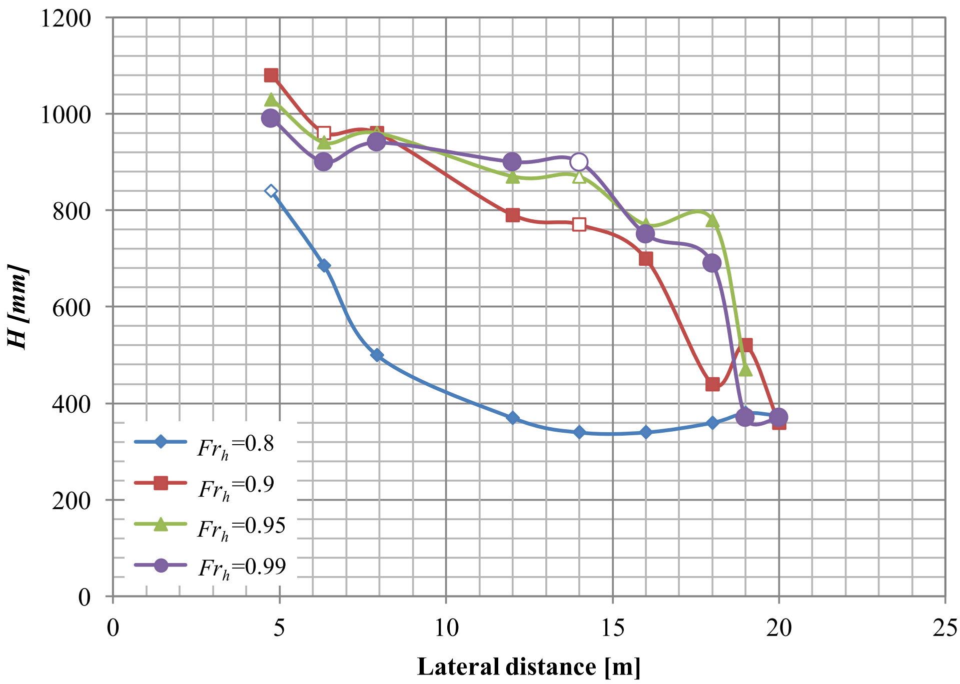


Fig. 11: Wave height at different lateral distances for various Depth Froude numbers for Channel 1

Table 1: **Wave height and water depth at wave breaking points for different Froude depth numbers for Channel 1**

Fr_h	Wave height at breaking point H [m]	Water depth at breaking point h [m]	H/h
0.8	0.84	3.75	0.224
0.9	0.94	3.75	0.25
	0.77	1.7	0.45
0.95	0.87	1.7	0.51
0.99	0.9	1.7	0.53

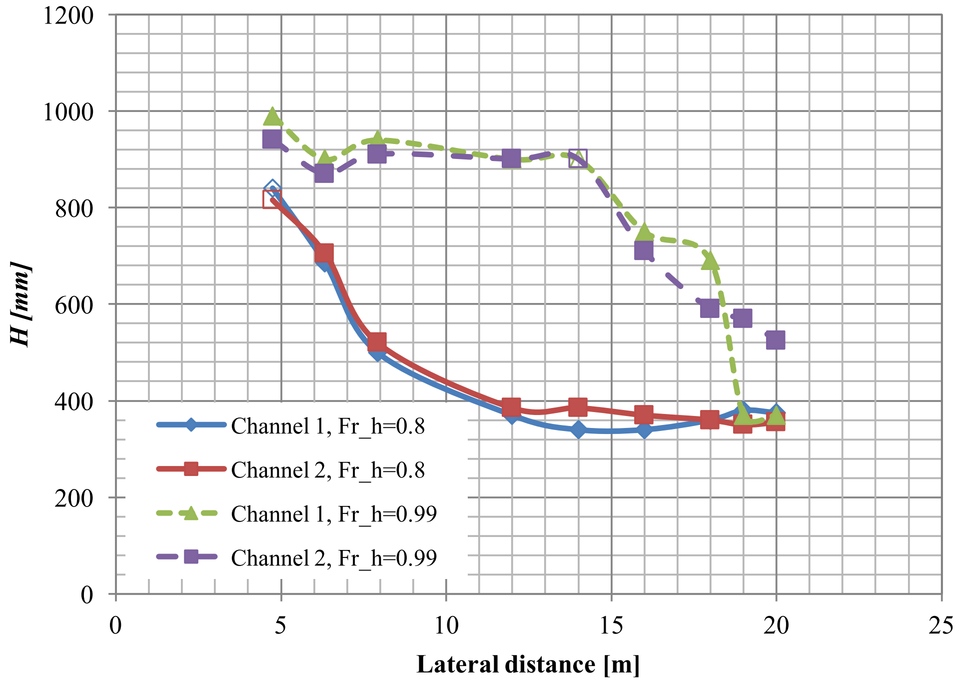


Fig. 12: Comparison of the results for two different channel configuration; channel 1 and channel 2, at Fr_h= 0.8

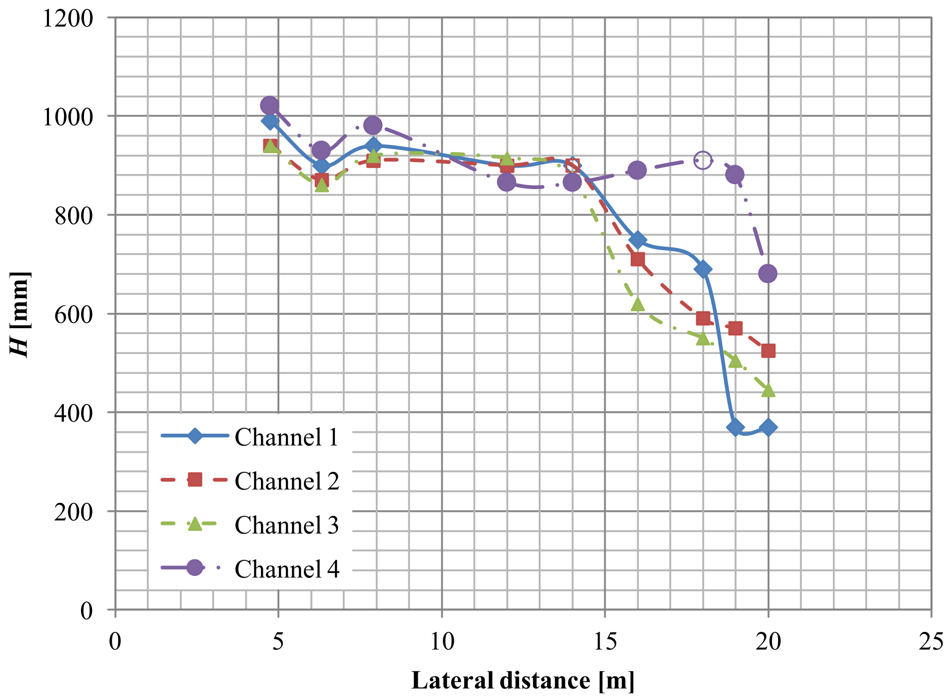


Fig. 13: Simulation results of wave height for different lateral distances for four channel configurations at $Fr_h = 0.99$.

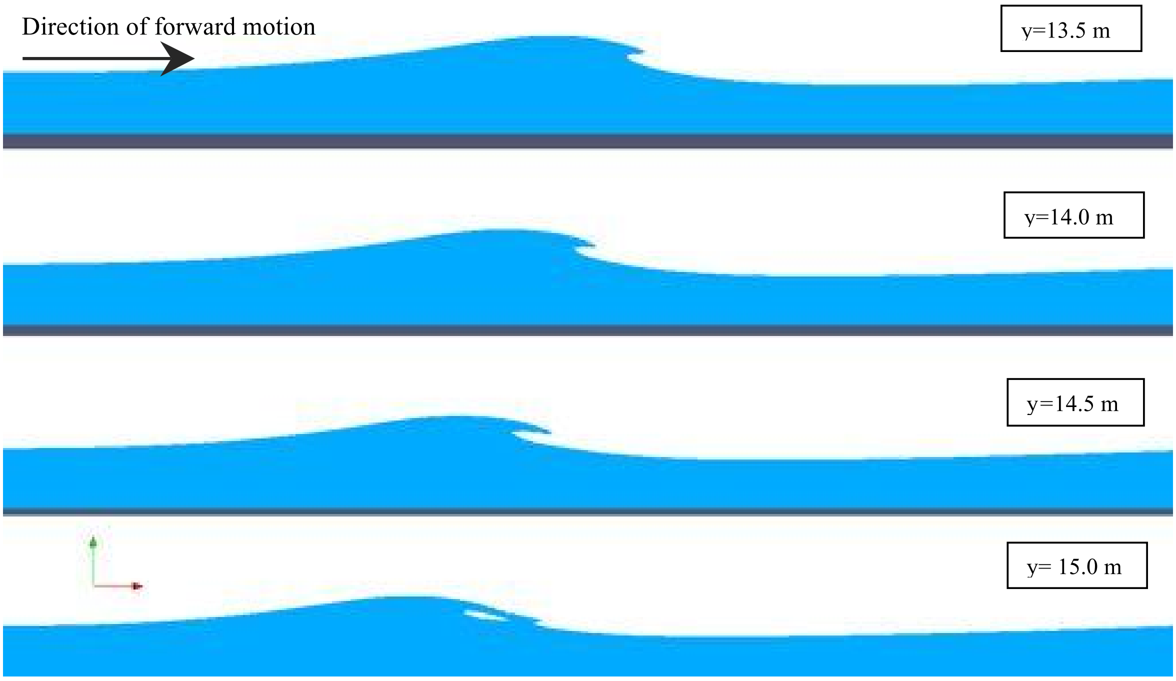


Fig. 14: Plunging shape of the wave for channel 3 at Fr_h=0.99 at different lateral distances

Table 2: Vortex ratio for different channel at Fr_h=0.99

	Vortex ratio
Channel 1	3.8
Channel 2	5
Channel 3	4.2
Channel 4	5.5

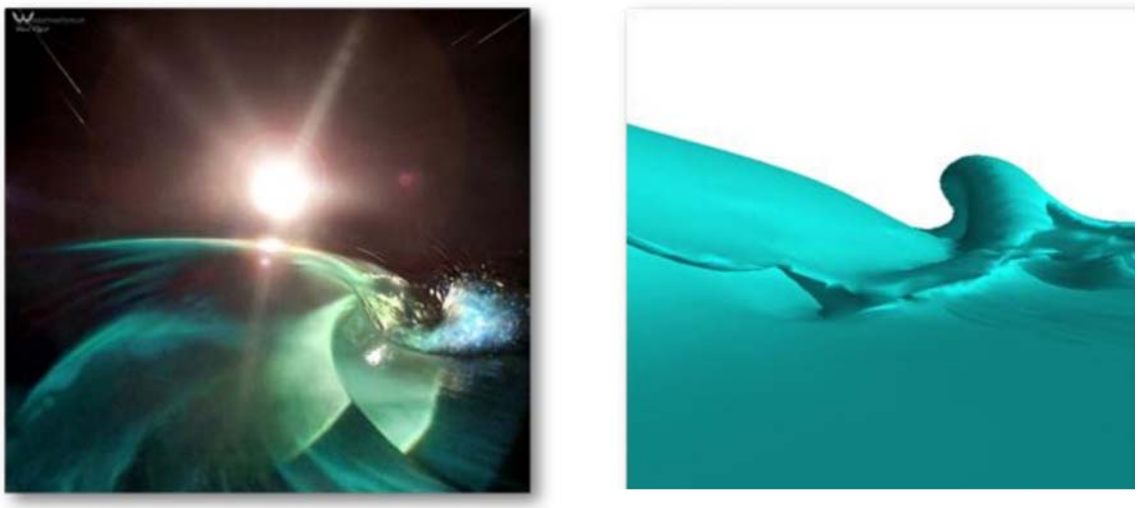


Fig. 15: **Comparison of experimental and numerical wave breaking shape**

Table 3: Average Peel Angle for Channel 1 for Different Fr_h

Fr_h	Average peel angle (degrees)	Average wave height (mm)	Surfing skill level
0.8	63	395	9
0.9	66	870	4
0.95	63	923	4
0.99	52	913	6

Table 4: Average Peel Angle for Different Channels at Fr_h=0.99

	Average peel angle (degrees)	Average wave height (mm)	Surfing skill level
Channel 1	52	913	6
Channel 2	52	903	6
Channel 3	52	903	6
Channel 4	54	898	7